NIRT: Self-Aligned and Self-Limited Quantum Dot Nanoswitches

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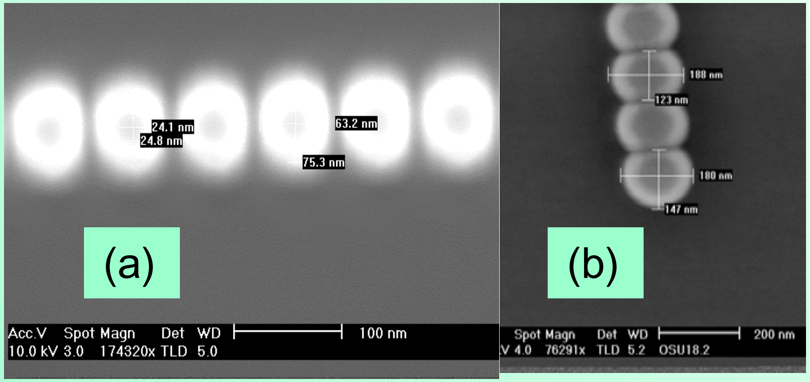

Fig. 1: A photomicrograph of the (a) discrete and (b) "clustered" nanoswitches. Swelling during the transformation leads to adjacent structures

●The objective of this project is to capitalize on slight differences in semiconductor properties of different candidate materials to realize a robust process for the synthesis of quantum dot nanoswitches (≤ 10 nm) for quantum functional computation.

●Challenges exist in exploring how matter manipulated at the nanoscale behaves differently than in bulk form and then measuring and quantifying those discrepancies.

●Linear arrays of nanopillars (25-100 nm diameters) have been directly written with nanoscale interactional distances (75-200 nm), and then processed to shrink the active area size down to below 10 nm. Electrical transport measurements, both electron and hole, are ongoing.

●The observed swelling during conversion by the NIRT team contradicts earlier reports. Currently dot-to-dot interactions have been shown to control dot shape, ellipsoidal versus circular (Fig. 2b). This nanoscale plasticity and reflow is currently under further study.

●A method is being developed for rapid and simple electron microscope sample preparation that does not adversely damage the nanoscale region of interest. An added benefit will be that the same samples used for TEM inspection can also be electrically characterized, allowing direct correlation between quantum dot shape/size and electrical performance.

Aim of the project:

The aim of this project is to fashion quantum dot nanoswitches of a predictable size and placement using a combination of direct patterning followed by oxidation/etching to reduce the dimensionality and encase the quantum dot in an oxide that will become a tunneling barrier for the addition and subtraction of charge onto the dot.

Significance of this work:

Conventional shrinking methods to improve VLSI chip performance through dense packing of circuit elements and miniaturization (scaling) of device and interconnect geometries in all three dimensions is predicted to continue until the gate lengths of transistors are on the order of 10 nm, thus encountering the ultimate “CMOS brick wall.” At ultra-small nanometric dimensions, quantum transportation of device charge carriers is likely to dominate the nonlinear behavior of the nanometric devices, manifesting folded-back resonant tunneling I-V characteristics.

Development of new materials properties and process technology is important to facilitate the manufacturability of quantum functional circuits. Challenges exist in exploring how matter manipulated at the nanoscale behaves differently than in bulk form and then measuring and quantifying those discrepancies.

Research results:

A large body of work was accomplished over the past year by the NIRT Team Members at Ohio State, Illinois at Urbana-Champaign, Notre Dame, and California at Riverside as well as our collaborative partner at the Naval Research Laboratory. An Annual NIRT Review of the team’s activities took place at Ohio State on November 10, 2003. Below is a snapshot of notable accomplishments over the past year. The next meeting is tentatively scheduled November 4, 2004 at Ohio State.

Linear arrays of nanopillars (25-100 nm diameters) have been directly written by electron beam lithography with nanoscale interactional distances (75-200 nm), and then processed to effectively shrink the active area size down to below 10 nm, preferably below 4 nm, the anticipated threshold for room temperature switching of single electrons. Samples with both n-type and p-type doped contacts have been fashioned and are currently undergoing electrical transport measurements, both electron and hole, below liquid helium temperatures to amplify the observed phenomenon.

The observed swelling of the three-dimensional nanopillars during conversion by the NIRT team contradicts earlier reports that suggested that no changes in dimensionality occurred. Currently dot-to-dot interactions have been shown to control dot shape, ellipsoidal versus circular (Fig. 2b) as the swelling causes the in-line distance to be fixed and the out-of-line distance to swell to accommodate the expansion This nanoscale plasticity and reflow is currently under further study and will be compared to bulk properties. Dot-to-dot interactions are shown to control the quantum dot shape from ellipsoidal versus circular, shown at the end of the row in Fig. 2(b). Quantum dot shape is also expected to control charging, tunneling and subsequently switching.

A promising method is being developed for rapid and simple electron microscope sample preparation that does not adversely damage the nanoscale region of interest. Previous methods using a focused ion beam were found to be too damaging when the nanopillar dimensions were reduced to well below 100 nm. An added benefit will be that the same samples used for TEM inspection can also be electrically characterized, allowing direct correlation between quantum dot shape/size and electrical performance.

The NIRT team succeeded in the development of submicron Si-based resonant interband tunnel diodes (RITD) that were iteratively measured and reduced in active device area. Scaling succeeded in achieving ~ 0.5 μm^2 devices. Concurrently, these devices broke the world record in Si-based interband tunnel diode current density achieved by this team last year. The ultra-small structures lend themselves nicely to high speed performance without sacrificing current drive capability.

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Education: The NIRT Team consists of 4 universities and 1 government laboratory. Six graduate students were supported which includes 2 who graduated and 2 replacements.

Outreach: Supplemental NSF Research Experiences for Undergraduates (REU) awards have been leveraged with other REU awards and matching funds from the Center for Materials Research to support 7 undergraduate researchers (2 girls/1 Hispanic) and 1 high school researcher (1 girl) during the Summer 2004. The NSF support has greatly strengthened a recent proposal submission for an NSF REU Site (PI: Berger) with OSU matching monies. This will potentially support 20 undergraduate students and establish an Undergraduate Research Institute within ECE.

Fig. 2: A graduate student has a technical discussion with an REU.

Fig. 3: An REU is synthesizing nanotowers of electroactive polymers using a template of mesoporous membranes

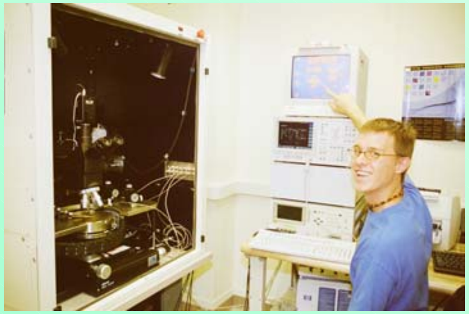

Fig. 4: (center) An REU takes electrical measurements of quantum tunneling devices, and (left) shows one of the volunteer high school researchers participating (Ms. Sarah Sheldon).